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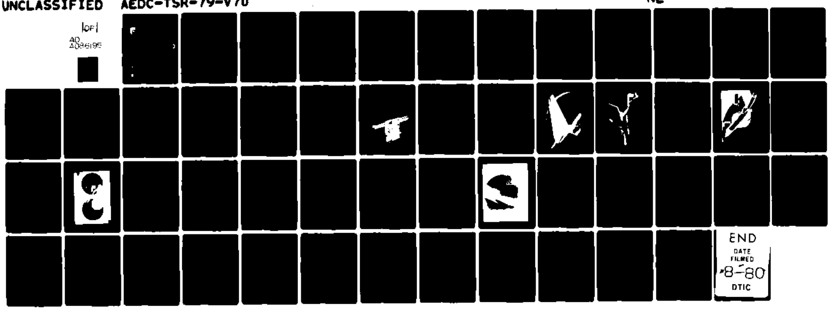

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SPACE SHUTTLE ORBITER SILTS POD FLOW ANGULARITY AND AERODYNAMIC HEATING (OH-102A AND OH-400)

K. W. Nutt

ARO, Inc.

ADA086195

November 1979

Final Report for Period October 1978 - October 1979

ARNOLD ENGINEERING DEVELOPMENT CENTER
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Joseph F. Pawlick

JOSEPH F. PAWLICK, Jr., Lt. Col, USAF
Test Director, VKF Division
Directorate of Test Operations

Approved for publication:

FOR THE COMMANDER

James D Sanders

JAMES D. SANDERS, Colonel, USAF
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READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (14) AEDC-TSR-79-V70	2. GOVT ACCESSION NO. AD-A086 195
3. RECIPIENT'S CATALOG NUMBER 9	
4. TITLE (and Subtitle) (6) SPACE SHUTTLE ORBITER SILTS POD FLOW ANGULARITY AND AERODYNAMIC HEATING TESTS (OH-102A AND OH-400),	5. TYPE OF REPORT & PERIOD COVERED Final Report, October 1978 – October 1979
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) K. W. Nutt ARO, Inc., a Sverdrup Corporation Company	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center/DO Air Force Systems Command Arnold Air Force Station, TN 37389	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 921E01
11. CONTROLLING OFFICE NAME AND ADDRESS NASA/Johnson Space Center (ES3) Houston, TX 77058	12. REPORT DATE (11) November 1979
	13. NUMBER OF PAGES 49
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 5	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in Defense Technical Information Center (DTIC).

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

heat transfer
oil flow
flow field probe
space shuttle orbiter
hypersonic testing
SILTS pod

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Heat transfer, flow field, and oil flow tests were conducted on a 0.0175 scale model of the space shuttle orbiter. The tests were conducted at Mach 8 ~~in the AEDC-VKF Hypersonic Tunnel B~~. The objective of the tests was to determine the aerodynamic heating distribution on the orbiter SILTS tail configuration and to obtain flow field total pressure and total temperature measurements at the location of the leading edge of the vertical tail. The tests were conducted at free-stream Reynolds numbers ranging from 0.5×10^6 to 3.7×10^6 per ft. The model angle of attack was varied from -5 to 5 deg and from 30 to 40 degrees.

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NOMENCLATURE

ALPHA	Model angle of attack, deg
ALPHA-PREBEND	Sting prebend angle, deg
ALPHA-SECTOR	Tunnel sector angle, deg
ALPT	Angle pitch drive unit makes with respect to the tunnel centerline, deg
b	Model skin thickness, in. or ft
BV	Height of model vertical tail (see Fig. 3), in.
CONFIG	Code used to define model configuration
CONSTANT SET	The set of thermocouples recorded during a tunnel injection (see Table 2)
c_p	Model skin material specific heat, Btu/lbm°R
CV	Vertical tail chord (see Fig. 3), in.
DTWDT	Time rate of change of wall temperature, °R/sec
FLOW ANGLE	Angle of flow with respect to the leading edge of the vertical tail (see Fig. 3), deg
GROUP	Data identification number
H_{local}	Local heat-transfer coefficient
HREF	Reference heat-transfer coefficient based on Fay and Riddell theory. See Appendix III
H(TO)	Heat-transfer coefficient based on TO (see Eq. 1), Btu/ft^2-sec-°R
H(0.9 TO)	Heat-transfer coefficient based on 0.9 TO, Btu/ft^2-sec-°R
MACH NO., M	Free-stream Mach number
MODEL	Model designation
MU-INF	Free stream viscosity, lbf-sec/ft^2
MUO	Viscosity conditions based on stagnation temperature, lbf-sec/ft^2

P-INF	Free-stream static pressure, psia
PO	Tunnel stilling chamber pressure, psia
PO2	Stagnation pressure downstream of a normal shock, psia
PPN	Total pressure measured by probe PPN, N = 1 or 2 (see Fig. 14), psia
QDOT	Heat-transfer rate, (w b c_p)(DTWDT), Btu/ft^2-sec
Q-INF	Free-stream dynamic pressure, psia
R	Radius of 0.0525 scale SILTS pod dome, R = 0.56 in., (see Fig. 11), in.
RE/FT	Free-stream Reynolds number
RHO-INF	Free-stream density, lbm/ft^3
RN	Reference nose radius, (0.0175 ft or 0.0525 ft, determined by model scale)
ROLL-SECTOR	Tunnel sector roll position, deg
S	Surface distance on 0.0525 scale SILTS pod (see Fig. 11)
SILTS SCALE	Scale of vertical tail on the OH-400 Test (0.0175 or 0.0525)
STFR	Stanton number based on HREF (see Appendix III)
SWITCH POSITION	Designates the position of the thermocouple selector switch
t	Time from start of model injection cycle, sec
t_i	Time when initial model wall temperature was recorded before model injection, sec
TC NO	Thermocouple number
THETA	Angular position of thermocouples on the SILTS pod of the 0.0525 scale vertical tail (see Fig. 11), deg

T-INF	Free-stream temperature, °R
TO	Tunnel stilling chamber temperature, °R
TTN	Total temperature measured by probe TTN, N = 1 or 2 (see Fig. 14), °R
TW	Model wall temperature at midpoint of data interval, °R
TW_i	Initial model wall temperature before injection, °R
V-INF	Free-stream velocity, ft/sec
w	Model skin material density, lbm/ft^3
X	Longitudinal coordinate of vertical tail (see Fig. 3), in.
XT	Tunnel longitudinal axis coordinate (see Fig. 12b), in.
Y	Lateral tunnel axis coordinate (see Fig. 12b), in.
YAW	Yaw angle of model, deg
Z	Model scale vertical coordinate (see Fig. 3), in.
ZT	Tunnel vertical axis coordinate (see Fig. 12a), in.

1.0 INTRODUCTION

The work reported herein was conducted at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was sponsored by the Johnson Space Center (NASA-JSC(ES3)), Houston, Texas, under Program Element 921E-01. Rockwell International (RI), Space Division, Downey, California was responsible for test planning and data analysis. The project monitor for NASA-JSC(ES3) was Mrs. Dorothy B. Lee and the test engineer for Rockwell International was Mr. Jim Collins.

The overall objective of the tests was to measure heat transfer coefficients on the SILTS* pod of a scaled space shuttle orbiter model. The SILTS pod houses an infrared sensor which will be used during flight tests to obtain orbiter leeside surface temperature distributions. Since the pod, which mounts on the top of the vertical tail, is in the wake of the orbiter, flow conditions approaching the tail are needed to permit data analysis and extrapolation to flight conditions. Therefore, flow angularity, local pitot pressure and local total temperature measurements were added to the usual heating rate measurements.

The test was conducted in two phases in the 50-in. diam Hypersonic Wind Tunnel (B) at the von Karman Gas Dynamics Facility (VKF). The first phase was an oil flow study to determine the flow angularity at the leading edge of the space shuttle orbiter vertical tail. This phase was designated by NASA/Rockwell International as the OH-102A test and was conducted on October 9, 25, and November 29, 1978. The objective of the second phase was to determine aerodynamic heating distributions on the orbiter SILTS tail configuration and to obtain total pressure and total temperature measurements at the leading edge of the vertical tail. This phase was designated as the OH-400 test and was conducted during the period October 5, 8 and 9, 1979. Both phases of the test were completed under ARO Project No. V41B-65.

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*Shuttle Infrared Leeside Temperature Sensor

The tests were conducted at a nominal Mach number of 8, with freestream Reynolds numbers varying between 0.5×10^6 and 3.7×10^6 per ft. Model angles of attack ranged from 30 to 40 deg for all phases of the test. In addition, heating distribution data were also obtained at angles of attack ranging from -5 to 5 deg.

Copies of all test data have been transmitted to Rockwell International. A data tape will be transmitted to Chrysler Corporation Space Division for their Dataman system. Inquiries to obtain copies of the test data should be directed to NASA-JSC(ES3), Houston, Texas 77058. A microfilm record has been retained in the VKF at AEDC.

2.0 APPARATUS

2.1 TEST FACILITY

Tunnel B (Fig. 1) is a closed circuit hypersonic wind tunnel with a 50-in. diam test section. Two axisymmetric contoured nozzles are available to provide Mach numbers of 6 and 8 and the tunnel may be operated continuously over a range of pressure levels from 20 to 300 psia at Mach number 6, and 50 to 900 psia at Mach number 8, with air supplied by the VKF main compressor plant. Stagnation temperatures sufficient to avoid air liquefaction in the test section (up to 1,350°R) are obtained through the use of a natural gas fired combustion heater. The entire tunnel (throat, nozzle, test section, and diffuser) is cooled by integral, external water jackets. The tunnel is equipped with a model injection system, which allows removal of the model from the test section while the tunnel remains in operation. A description of the tunnel may be found in Ref. 1.

2.2 TEST ARTICLES

2.2.1 Flow Angularity Test (OH-102A)

The flow angularity data for the OH-102A test were obtained using the Rockwell 56-ϕ model. This model was a 0.0175 scale phase change paint model that was modified by the addition of a new vertical tail. The new vertical tail was constructed of stainless steel with the pilot's left side being a flat slab that was coincident with the orbiter centerline. A sketch of the 56-ϕ model installation in the tunnel is presented in Fig. 2. The tip of the vertical tail extends past the theoretical tip (Z = 14.275 in.) to station Z = 15.025 in. as shown in Fig. 3. The tail extends past the theoretical tip to study the flow angle in the area of the SILTS pod. A photograph of the vertical tail with a typical oil flow pattern is shown in Fig. 4.

2.2.2 SILTS Pod Test (OH-400)

The model used for the OH-400 test was the 0.0175 scale Rockwell 92-ϕ orbiter model fitted with two different vertical tails. A photograph of the two vertical tail configurations is shown in Fig. 5. One configuration was a 0.0175 scale of the vertical tail and the SILTS pod. The second configuration was a 0.0525 scale vertical tail and SILTS pod that was truncated at the trailing edge to conform to the 0.0175 scale outline. A sketch comparing the outlines of these two configurations is shown in Fig. 6. The centerline of the 0.0525 scale SILTS pod is at the full span of the 0.0175 scale tail. The larger scale SILTS pod was tested to gain better definition of the heating distribution on the SILTS pod. Both vertical tail configurations were fabricated from 17-4PH stainless steel and instrumented with thermocouples. A photograph of the 92-ϕ model with the 0.0525 scale vertical tail installed is shown in Fig. 7. A sketch of the 92-ϕ model installation for both angle of attack ranges is presented in Fig. 8.

The 92-ϕ model was also used during the total pressure and total temperature probe phase. For these measurements the vertical tail was removed and a cover plate inserted to provide a smooth contour. A photograph of the 92-ϕ model installed for the probe phase is shown in Fig. 9.

2.3 TEST INSTRUMENTATION

The instrumentation, recording devices, and calibration methods used to measure the primary tunnel and test data parameters are listed in Table 1a along with the estimated measurement uncertainties. The range and estimated uncertainties for primary parameters that were calculated from the measured parameters are listed in Table 1b.

The model temperatures were measured with Chromel®-constantan thermocouples. The 0.0175 scale vertical tail and SILTS pod was instrumented with 43 thermocouples. The thermocouple locations are shown in Fig. 10 with coordinates and skin thicknesses listed in Table 2a. Thermocouples are on the pilot's left side of the tail. The 0.0525 scale vertical tail and SILTS pod was instrumented with 77 thermocouples. The locationsof these thermocouples are shown in Fig. 11 with coordinates and skin thicknesses presented in Table 2b. Thermocouples were located symmetrically about the SILTS pod but are only located on the pilot's left side of the tail.

The flow field measurements were obtained by using the overhead probe drive system illustrated in Fig. 12 that was designed and fabricated by the VKF. The unit is designated the "X-Y-Z" probe drive and can be mounted above the window opening on top of either Tunnel B or C. The X-Y-Z drive motors are located on top of the tunnel. In addition, the mechanism has the capability for pitching the probe holder 10 to -25 deg (ALPT) relative to the tunnel centerline. To minimize pressure stabilization time, the pressure transducers were mounted as close to the probes as possible in the area provided behind the water cooled shield.

Two total pressure (PP1 and PP2) probes were used during the flow field measurement. The two total pressure probes were fabricated from 0.0937 in. OD 1/4 hard stainless steel with a 0.015 in. wall thickness. The tip of the probe had a 15 deg bevel relative to the outer surface of the probe. Each probe was connected to a 15-psid Druck model PDCR-22 differential pressure transducer that was calibrated for 1-psid and 10-psid full scale. A near-vacuum reference pressure was used in conjunction with the differential pressure transducers. The reference pressure was measured with a Hastings absolute pressure transducer.

Two total temperature probes were used to measure the local stagnation temperature. These were single shielded thermocouple probes with a Chromel®- Alumel® thermocouple. The probe dimensions are presented in Fig. 13.

A special probe holder was fabricated to mount the pressure and temperature probes. A sketch of the probe holder is shown in Fig. 14. The probes were mounted in the tunnel with a 22 deg prebend when ALPT was zero. The position of PP1 was set at the centerline of the tunnel when the probe drive reading of Y equaled zero.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS AND PROCEDURES

3.1.1 General

The test was conducted at a nominal Mach number of 8 in Tunnel B. A summary of the specific test conditions is given below.

MACH No.	PO, psia	TO, °R	Q-INF, psia	P-INF, psia	RE/FTx10^{-6}
7.90	100	1250	0.5	0.01	0.5
7.94	205	1250	1.0	0.02	1.0
7.98	435	1300	2.0	0.05	2.0
7.99	670	1320	3.1	0.07	3.0
8.00	850	1350	3.9	0.09	3.7

A more detailed test summary showing all configurations tested and the variables for each is presented in Table 3.

In the VKF continuous flow wind tunnels (A, B, C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run, if necessary. The sequence is repeated for each configuration change.

3.1.2 Data Acquisition

Oil flow photographs were taken with Varitron Model E 70mm sequence cameras mounted outside the test section windows. Three cameras were used to provide photographic data on the OH-102A test and only one camera was used on the OH-400 test. An automatic camera control system was utilized to provide automatic shutter sequencing of 1 or 2 sec intervals.

The initial step prior to recording the thin-skin thermocouple data was to cool the model uniformly to approximately 70°F with high pressure air. Once the cooling cycle was complete, the desired model attitude was established in the tank prior to injection. With the desired tunnel free stream conditions established, the model was then injected into the tunnel. At lift-off, the initial temperature, (TW_i), for each thermocouple of the selected Constant Set was recorded. The data acquisition sequence was initiated at lift-off and continued for approximately 4 seconds after the model reached tunnel centerline. After each injection, the model was retracted and the cycle was repeated to cool the model to an isothermal state.

A Beckman® 210 analog-to-digital converter was used in conjunction with a Digital Equipment Corp.® (DEC) PDP-11 computer and a DEC-10 computer to record the temperature data. The Beckman® converter sampled the output of each thermocouple approximately 15 times per second.

The flow field measurements were made with the probe tips positioned in the plane of the leading edge of the vertical tail. Since the vertical tail was removed for these measurements, the following procedure was employed. An optical overlay of the vertical tail was marked with a grid showing the value of Z/BV as a percentage of the leading edge distance. A photograph of the model with the overlay superimposed is presented in Fig. 15. This overlay was mounted on an adjustable plate in the schlieren system and was aligned with the model. During the alignment, the 0.0175 scale vertical tail was installed on the model and the overlay was properly marked to insure that the overlay was coincident with the tail leading edge. The Y position of the probe drive was calibrated so that when probe PP1 was aligned with the centerline of the vertical tail, the value of Y equalled zero

Two types of probe measurements were recorded during the OH-400 test. The first type of probe measurements were freestream calibrations. These data were obtained with the model removed from the tunnel. With the probes in the tunnel freestream the probe angle with respect to the tunnel centerline was varied from -3 to 21 degrees in 3 deg increments. At each position the value of both pressure and both temperature probes were recorded. This provided a calibration of the probe sensitivity to flow angle misalignment. The second type were the probe measurements at the plane of the leading edge. With the model positioned in the tunnel at the desired angle of attack the overlay was adjusted to align with the model. The desired probe angle at each position with relation to the leading edge of the vertical tail was determined from the oil flow photographs on the OH-102A test. These angles are listed in Table 4. For each position along the leading edge (Z/BV) the desired probe angle was set and then the probe tip was driven to the desired Z/BV location. All four probe measurements (2 pressure, 2 temperature) and a photograph as shown in Fig. 15, were recorded for each data point.

3.2 DATA REDUCTION

The reduction of thin-skin thermocouple data utilizes the calorimeter heat balance, which, in coefficient form is

$$H(TO) = wbc_p \frac{DTWDT}{TO-TW} \tag{1}$$

Radiation and conduction losses are neglected in this heat balance, and data reduction simply requires evaluation of DTWDT from the temperature-time data and determination of model material properties. For the present tests, radiation effects were negligible; however, conduction effects were potentially significant in several regions of the model. To permit identification of these regions and improve evaluation of the data, the following procedure was used.

Separation of variables and integration of Eq, (1), assuming constant w, b, c_p and TO yields

$$\frac{H(TO)}{wbc_p}(t - t_i) = \ln\left[\frac{TO-TW_i}{TO-TW}\right] \tag{2}$$

Since $H(TO)wbc_p$ is a constant, plotting $\ln\ (TO-TW_i)/(TO-TW\ )$ versus time will give a straight line if conduction is negligible. Thus, deviations from a straight line can be interpreted as conduction effects.

The data were evaluated in this manner and, generally, a reasonably linear portion of the curve could be found for all thermocouples. A linear least-squares curve fit of $\ln\ (TO-TW_i)/(TO-TW)$ versus time was applied to the data. The data reduction time is typically started at centerline. However, the data for the thermocouples on the vertical tail leading edge were reduced starting 0.5 seconds prior to centerline for the 0.0175 scale tail and 0.61 seconds prior to centerline for the 0.0525 scale tail. This was done to reduce the data on these thermocouples before conduction errors became significant. The curve fit extended for a time span which was a function of the heating rate, as shown on the following list.

Range	Number of Points	Time Span, sec
DTWDT > 32	5	0.27
16 < DTWDT ≤ 32	7	0.41
8 < DTWDT ≤ 16	9	0.54
4 < DTWDT ≤ 8	13	0.82
2 < DTWDT ≤ 4	17	1.09
1 < DTWDT ≤ 2	25	1.63
DTWDT ≤ 1	41	2.72

In general, the time spans given above were adequate to keep the evaluation of the right-hand side of Eq. (2) within the linear region. The value of c_p is not constant, as assumed, and the relation

$$c_p = 0.0797 + (5.556 \times 10^{-5})\ TW,\ \text{(17-4 PH stainless steel)} \qquad (3)$$

was used with the computed value of TW at the midpoint of the curve fit. The maximum variation of c_p over any curve fit was less than 1.5 percent. Thus, the assumption of constant c_p was reasonable. The value of density used for the 17-4 PH stainless steel skin was, $w = 490\ lbm/ft^3$, and, the skin thickness, b, for each thermocouple is listed in Table 2.

The heat-transfer coefficient calculated from Eq. 2 was normalized using the Fay-Riddell stagnation point coefficient, HREF, based on a nose radius of 1.0 foot (scaled down to the scale of the vertical tail, i.e. RN = 0.0175 or 0.0525). (see Appendix III)

The pressure transducers used for the probe measurements were calibrated prior to each operational shift, and as required,with a known pressure differential and their readings recorded. A zero pressure differential is applied across each transducer and the zero readings are recorded. From these data scale factors for each transducer for each range are calculated. Probe pressures are calculated from differential pressure readings using the calibrated scale factors, plus a reference pressure (near vacuum).

3.3 UNCERTAINTY OF MEASUREMENTS

In general, instrumentation calibrations and data uncertainty estimates were made using methods recognized by the National Bureau of Standards (NBS). Measurement uncertainty is a combination of bias and precision errors defined as:

$$U = \pm (B + t_{95}S)$$

where B is the bias limit, S is the sample standard deviation, and t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution (95-percent confidence interval), which for sample sizes greater than 30 is taken equal to 2.

Estimates of the measured data uncertainties for this test are given in Table 1a. The data uncertainties for the measurements are determined from in-place calibrations through the data recording system and data reduction program.

Propagation of the bias and precision errors of measured data through the calculated data was made in accordance with Ref. 2 and the results are given in Table 1b.

4.0 DATA PACKAGE PRESENTATION

Oil flow photographs and plots of flow angle as a function of the percentage of distance along the vertical tail leading edge were transmitted to Rockwell at the completion of the OH-102A test. A typical oil flow photograph was presented in Fig. 4.

The final tabulated heating and flow field probe data were transmitted with this report to NASA-JSC and Rockwell International. The oil flow photographs obtained on the OH-400 test have been sent to Rockwell International. Sample tabulated data of the heat transfer and flow field probe measurements are presented in Appendix IV.

Representative data, along with the leading edge of the 0.0525 scale vertical tail and SILTS pod, are presented in Fig. 16. Data from two groups are presented as a sample of data repeatability. Representative data from the probe measurements are presented in Fig. 17.

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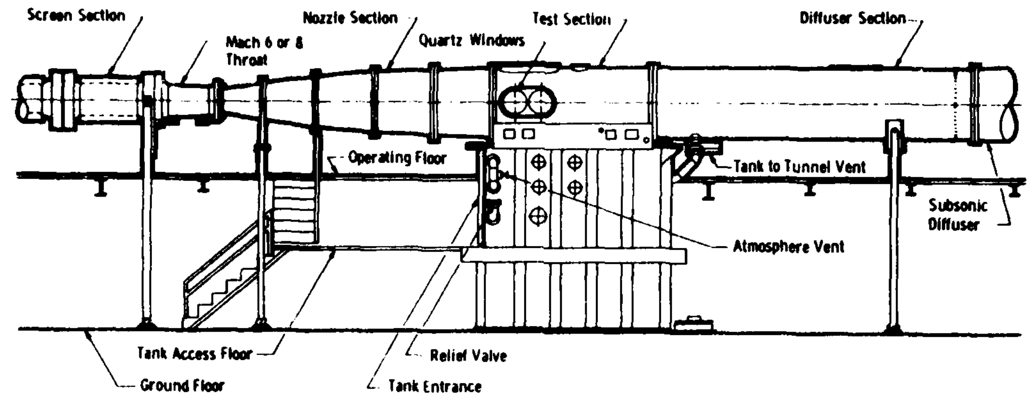
1. Test Facilities Handbook (Eleventh Edition). "von Karman Gas Dynamics Facility, Vol. 3." Arnold Engineering Development Center, June 1979.

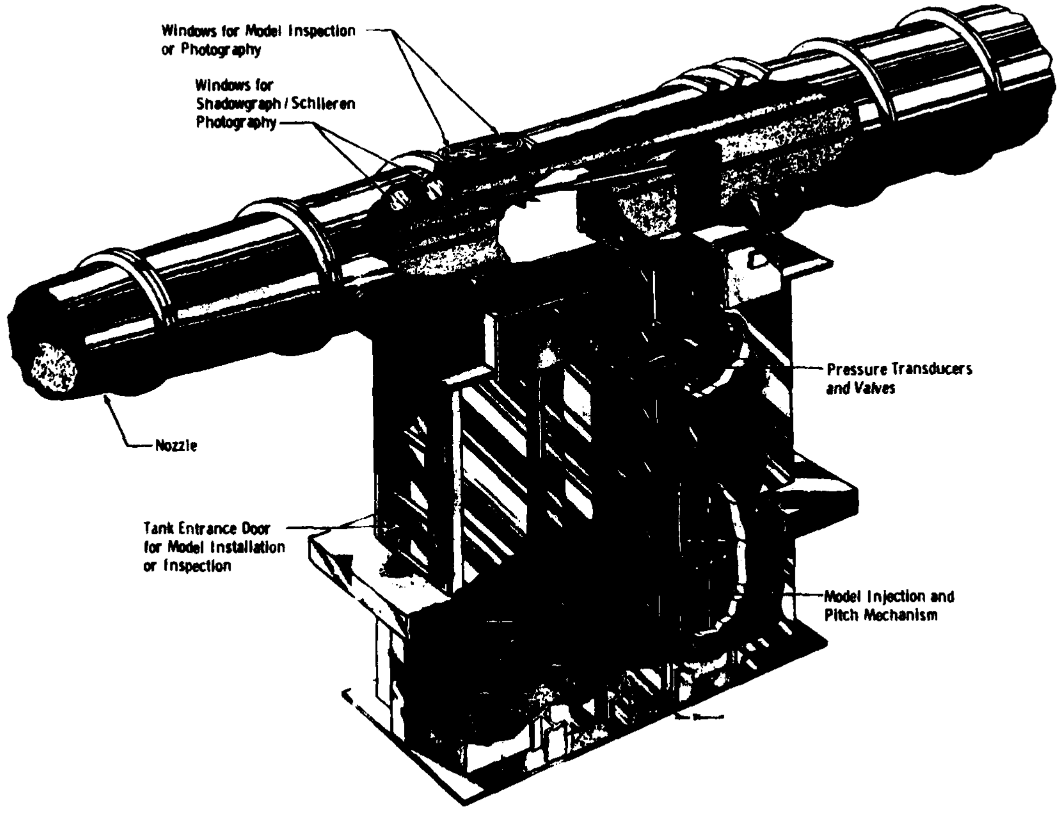
2. Abernethy, R. B. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD755356), February 1973.

APPENDIX I

ILLUSTRATIONS



a. Tunnel assembly



b. Tunnel test section

Fig. 1. Tunnel B

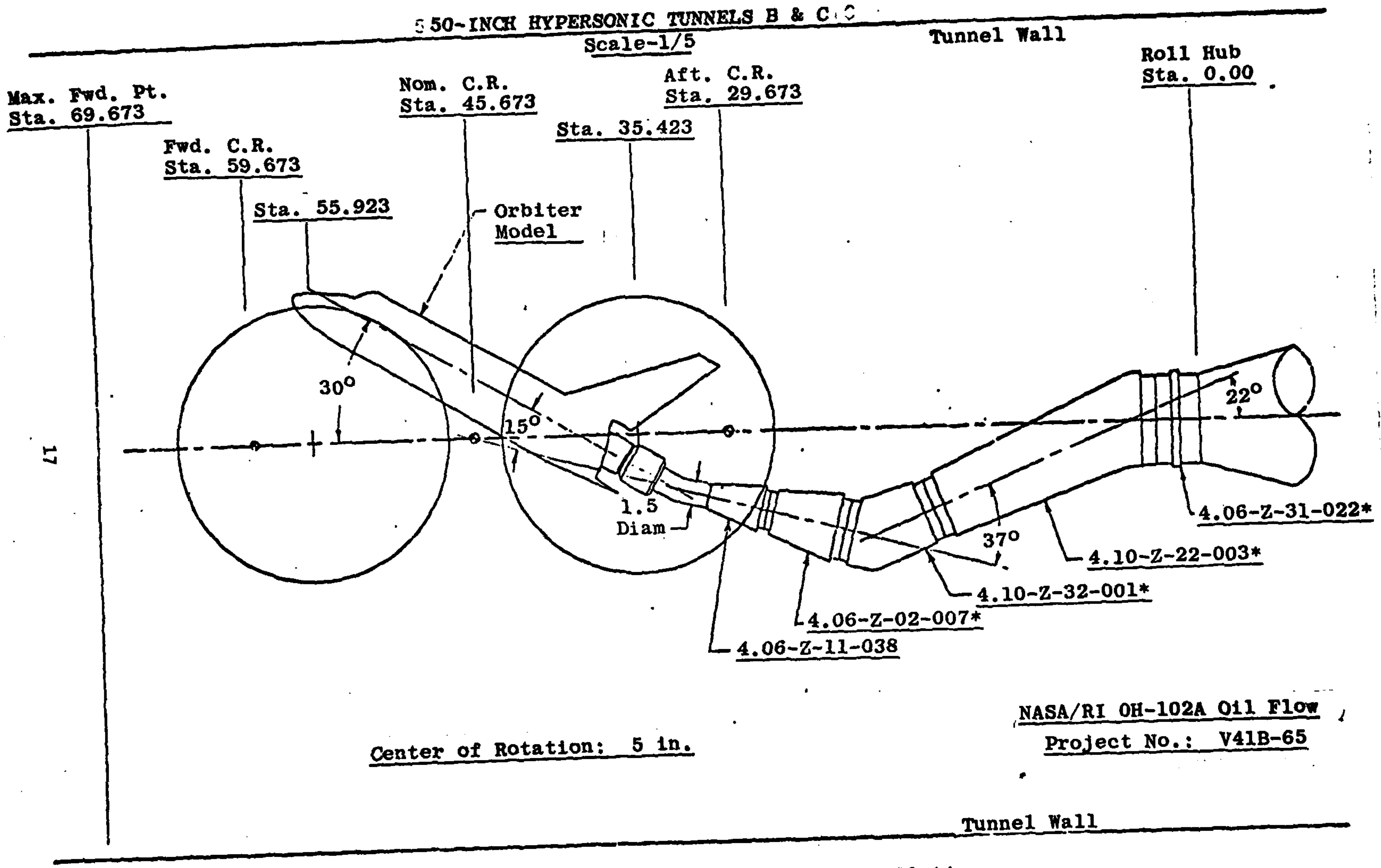


FIGURE 2. 56-Ø Model Installation

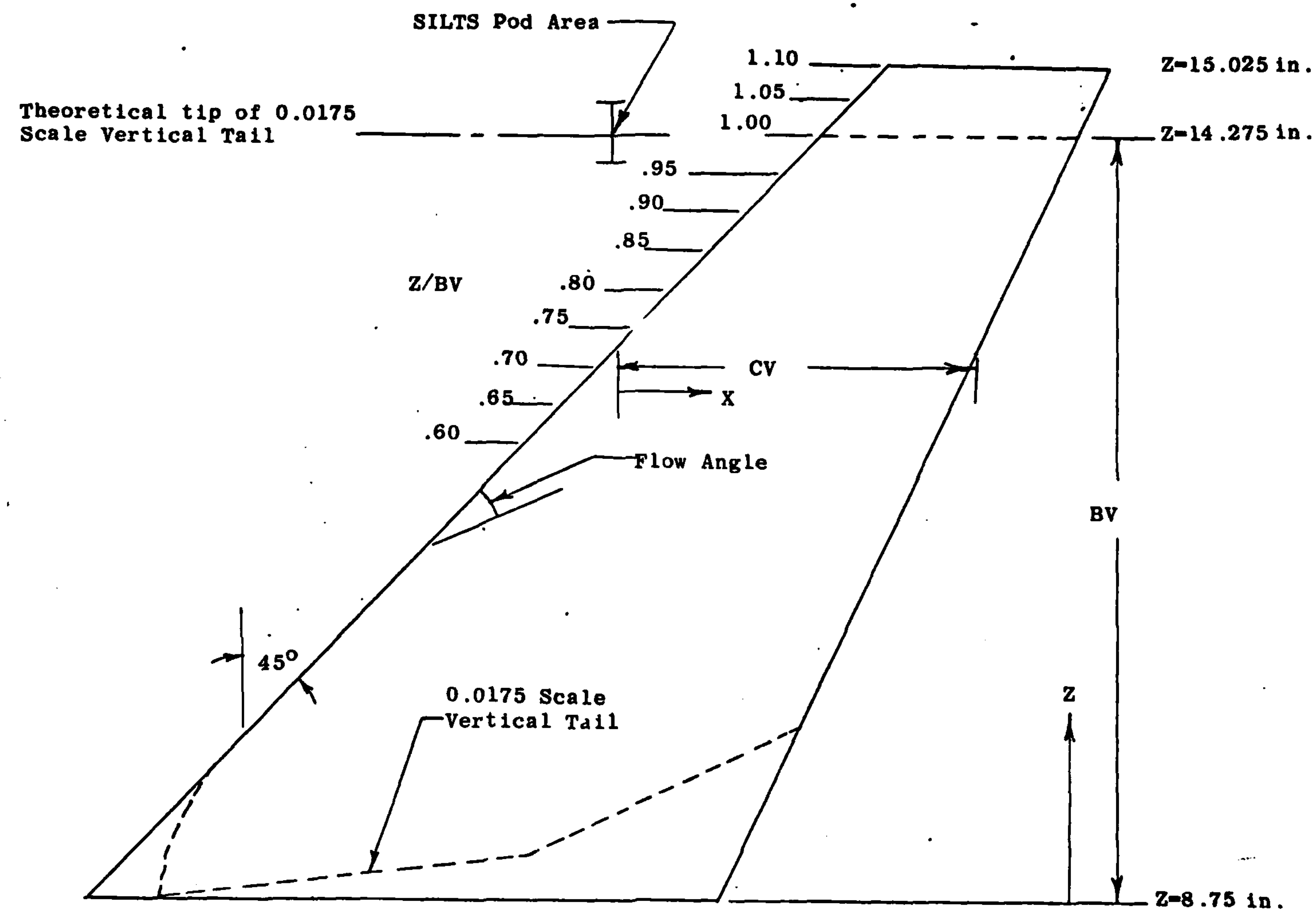


Fig. 3 Vertical Tail for Flow Angularity

Fig. 4 Photograph of 56-Ø Model Vertical Tail

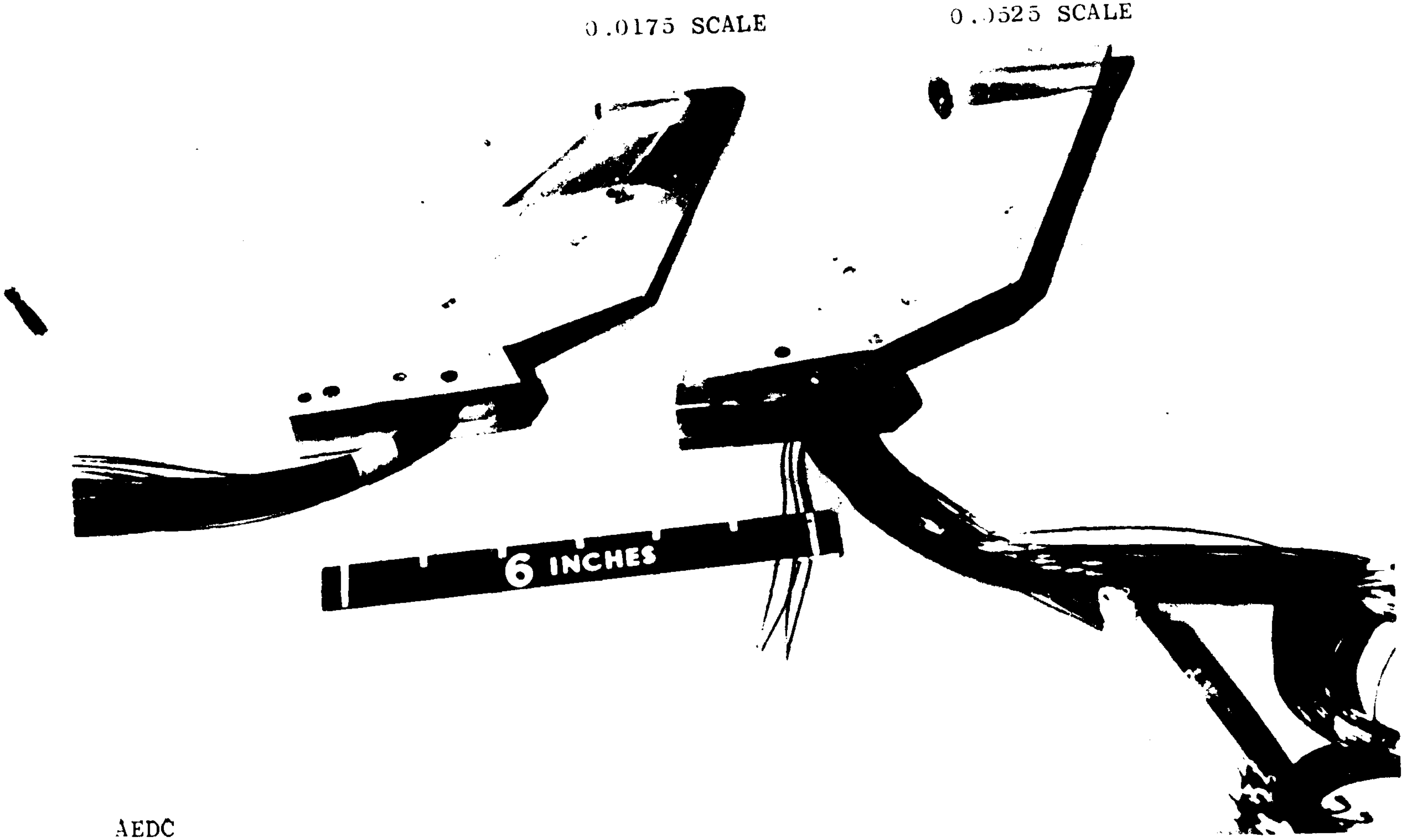


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Fig. 5 Photograph of 92-Ø Model Vertical Tail Configurations

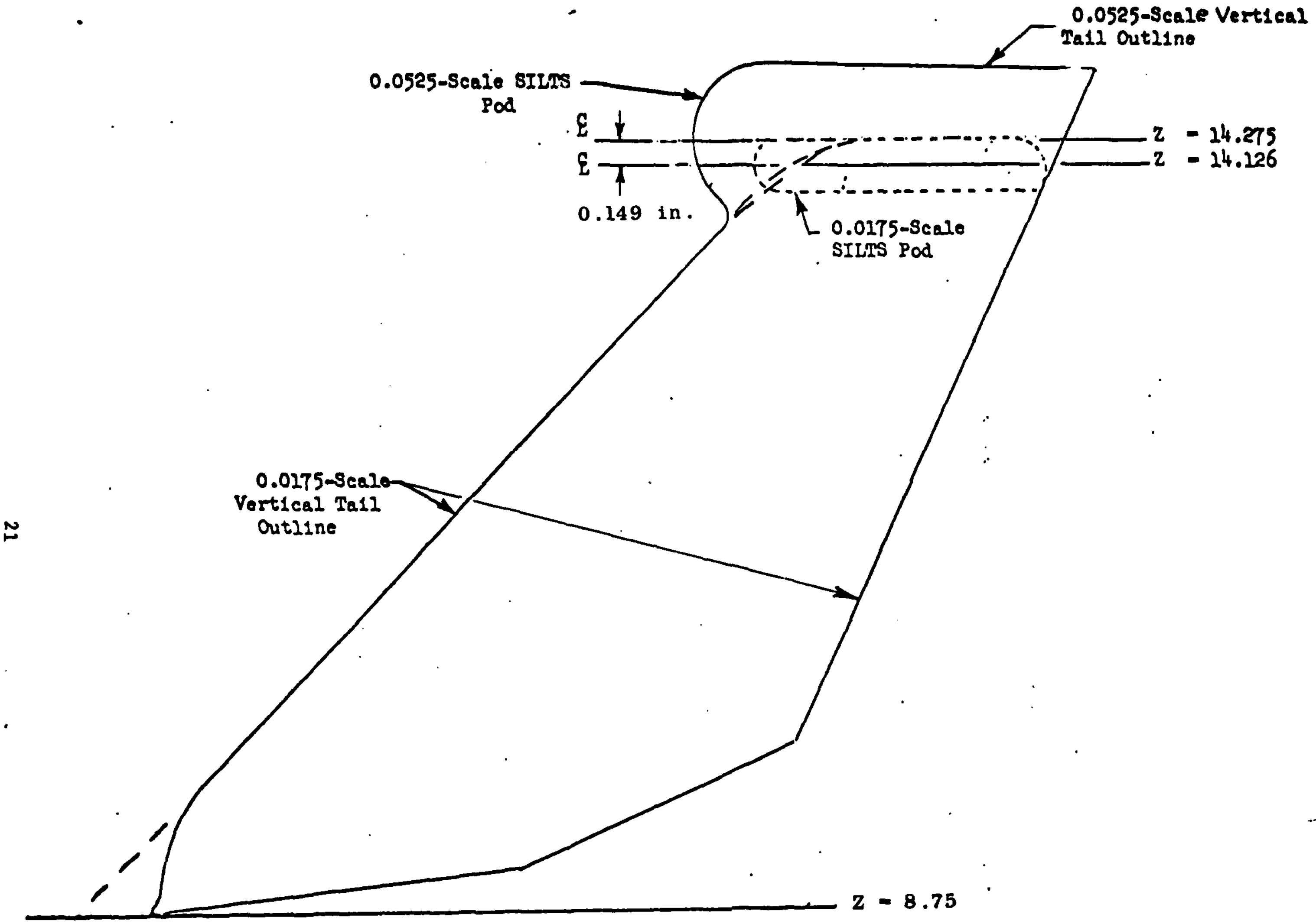
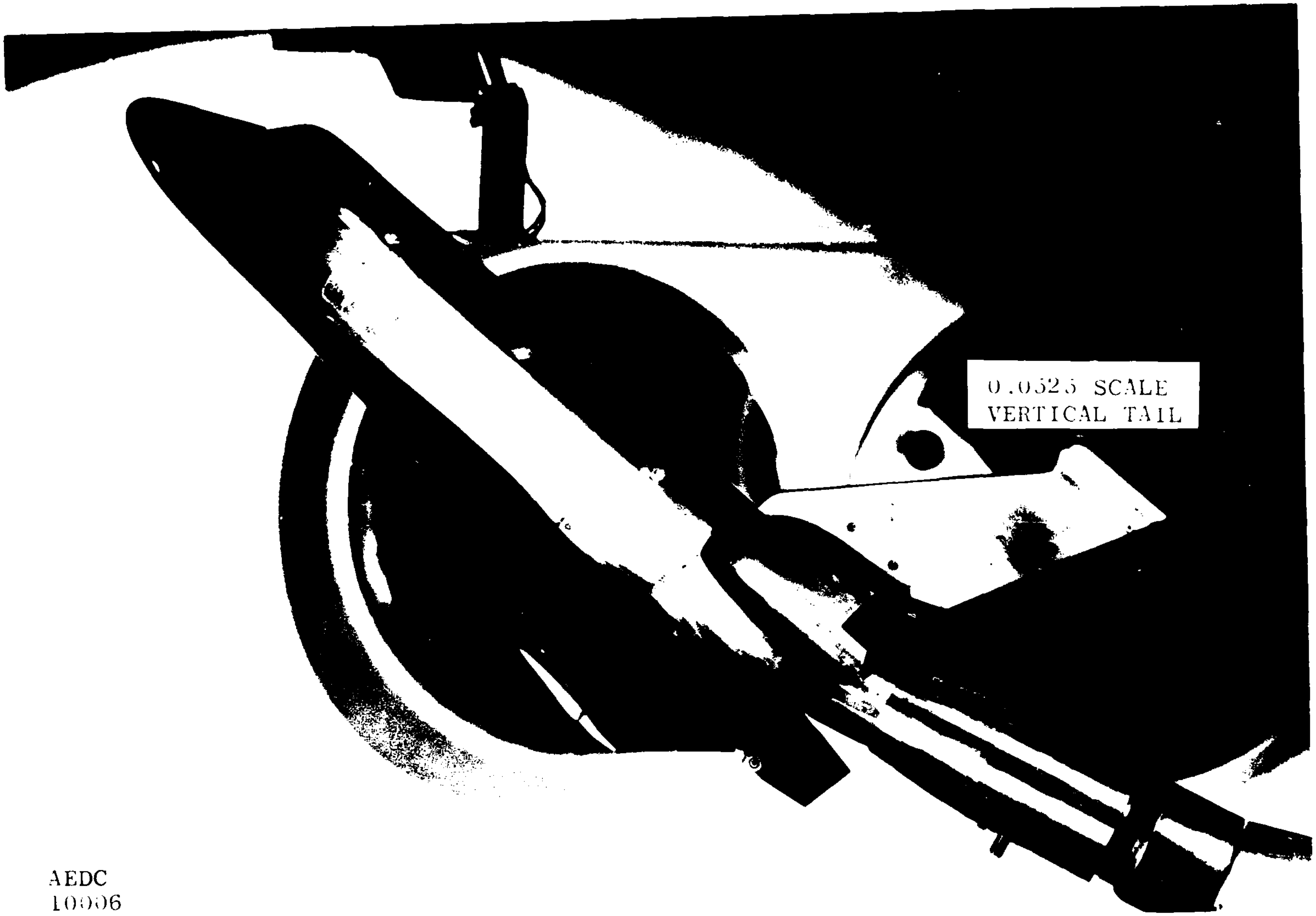
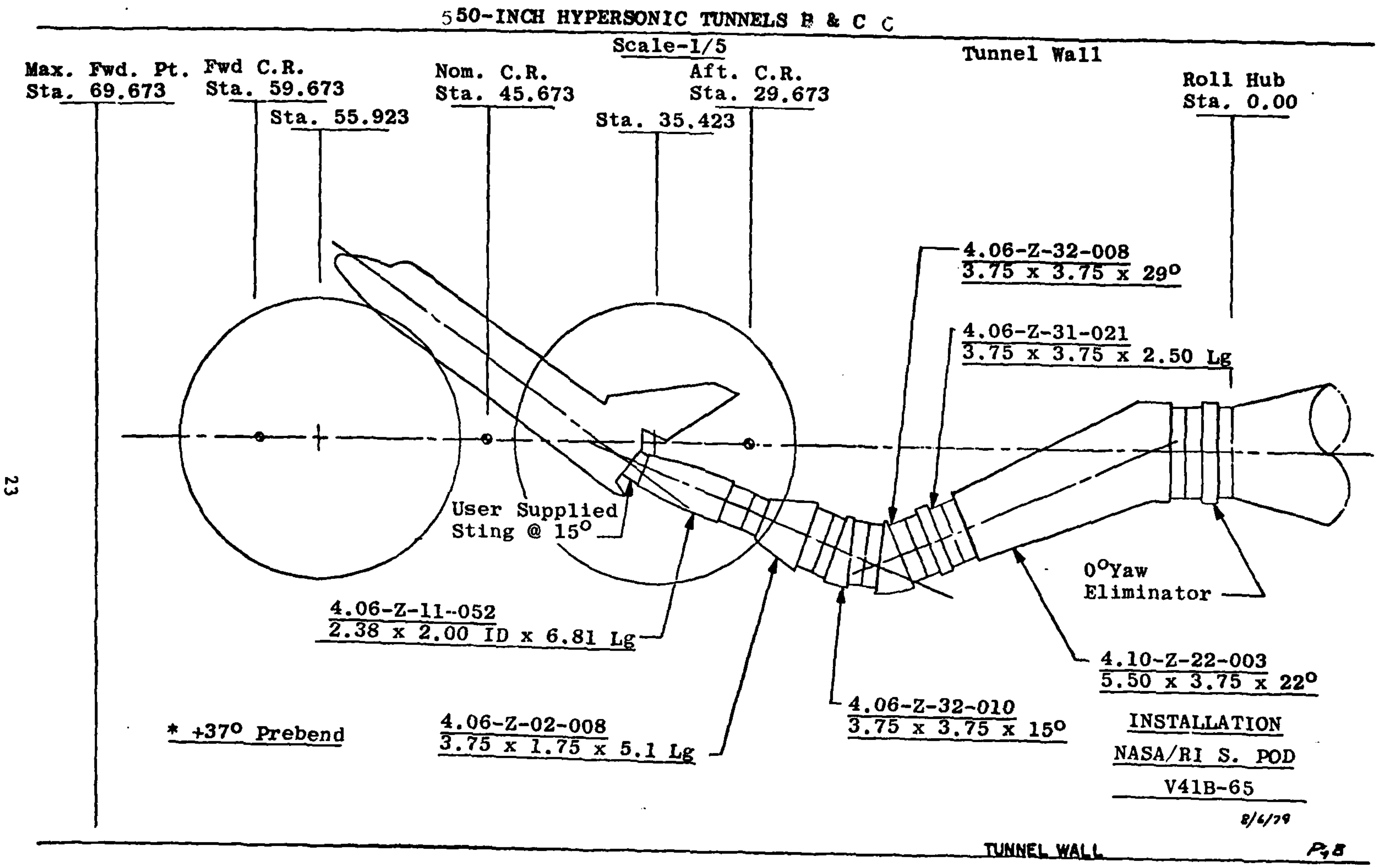


Fig. 6 Comparison of Vertical Tail Configurations



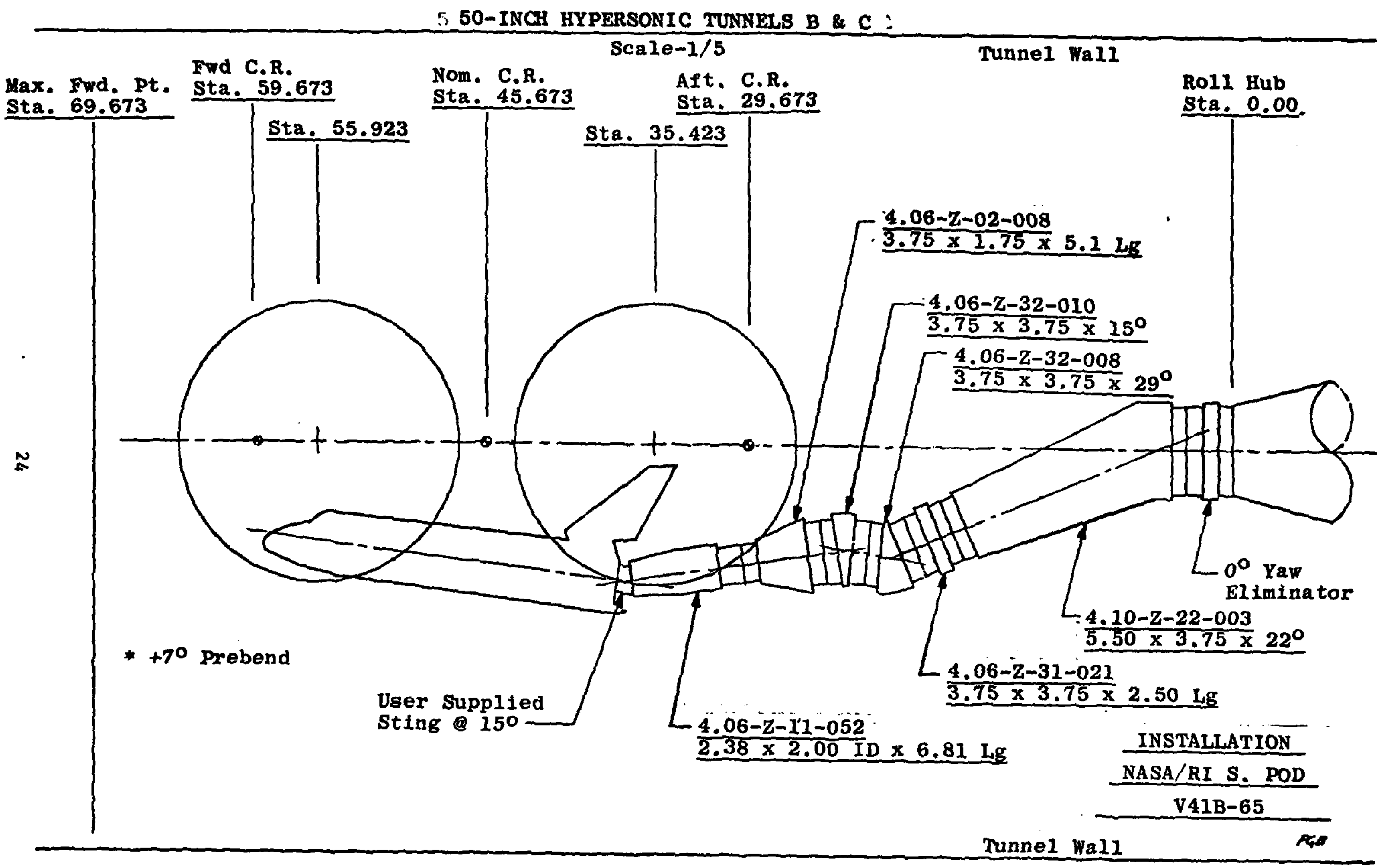
AEDC
10006

Fig. 7 Photograph of 92-0 Model Installation



a. 30 to 40 deg Angle of Attack Range

Fig. 8 92-Ø Model Installation



b. -5 to 5 deg Angle of Attack Range

Fig. 8. Concluded

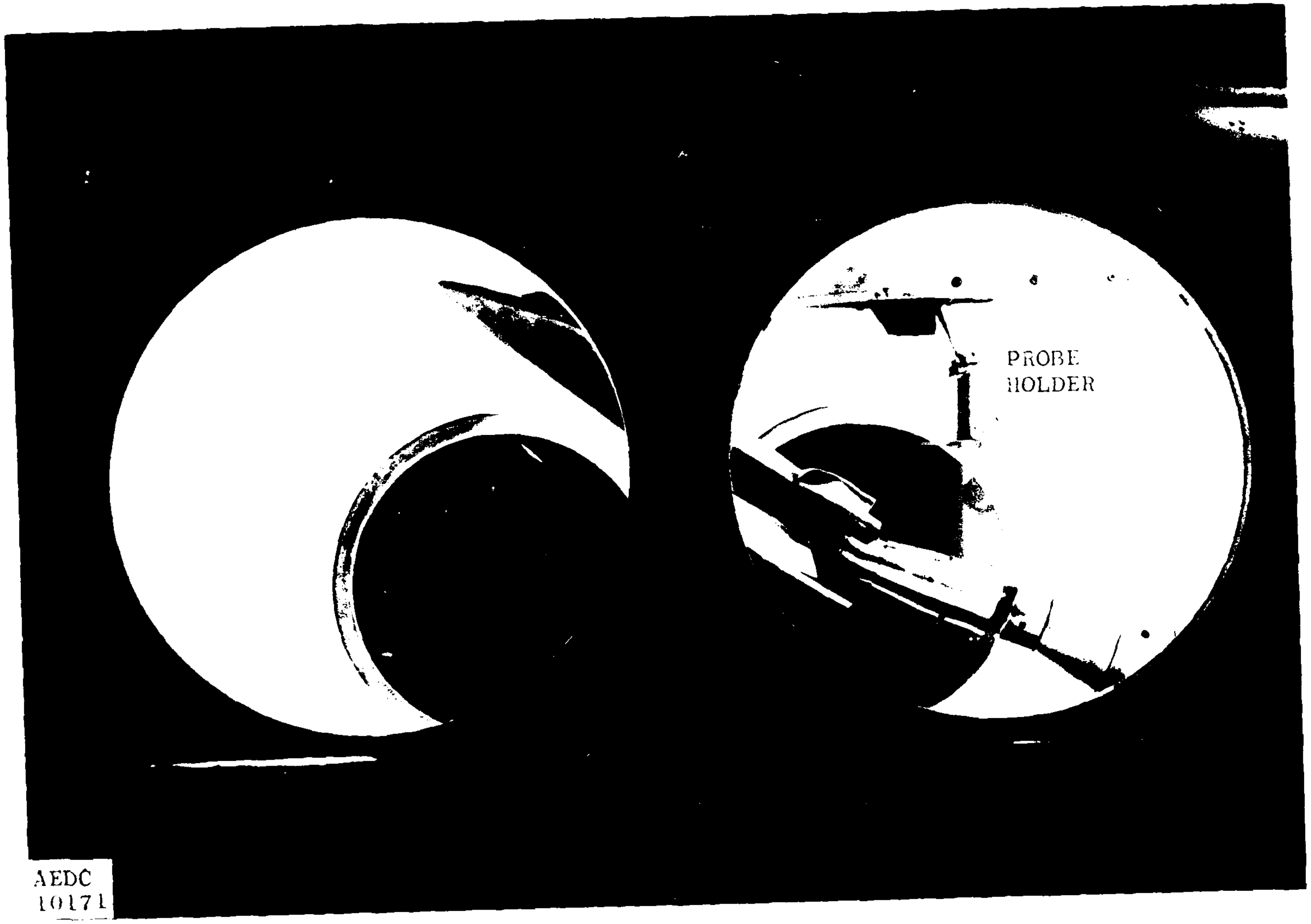


Fig. 9 Photograph of 92-0 Model Installation for Probe Phase

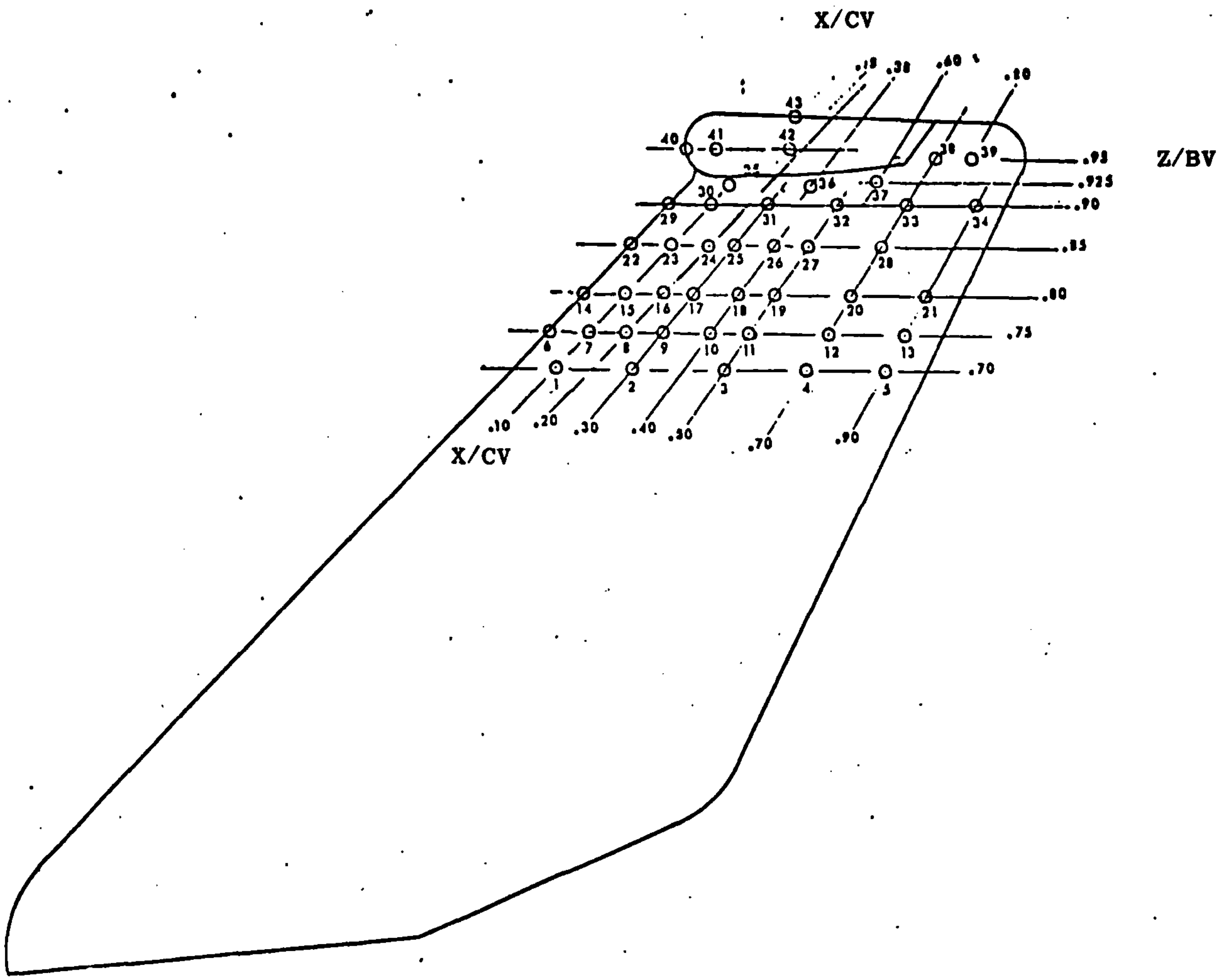


Fig. 10 Thermocouple Locations on 0.0175 Scale Vertical Tail

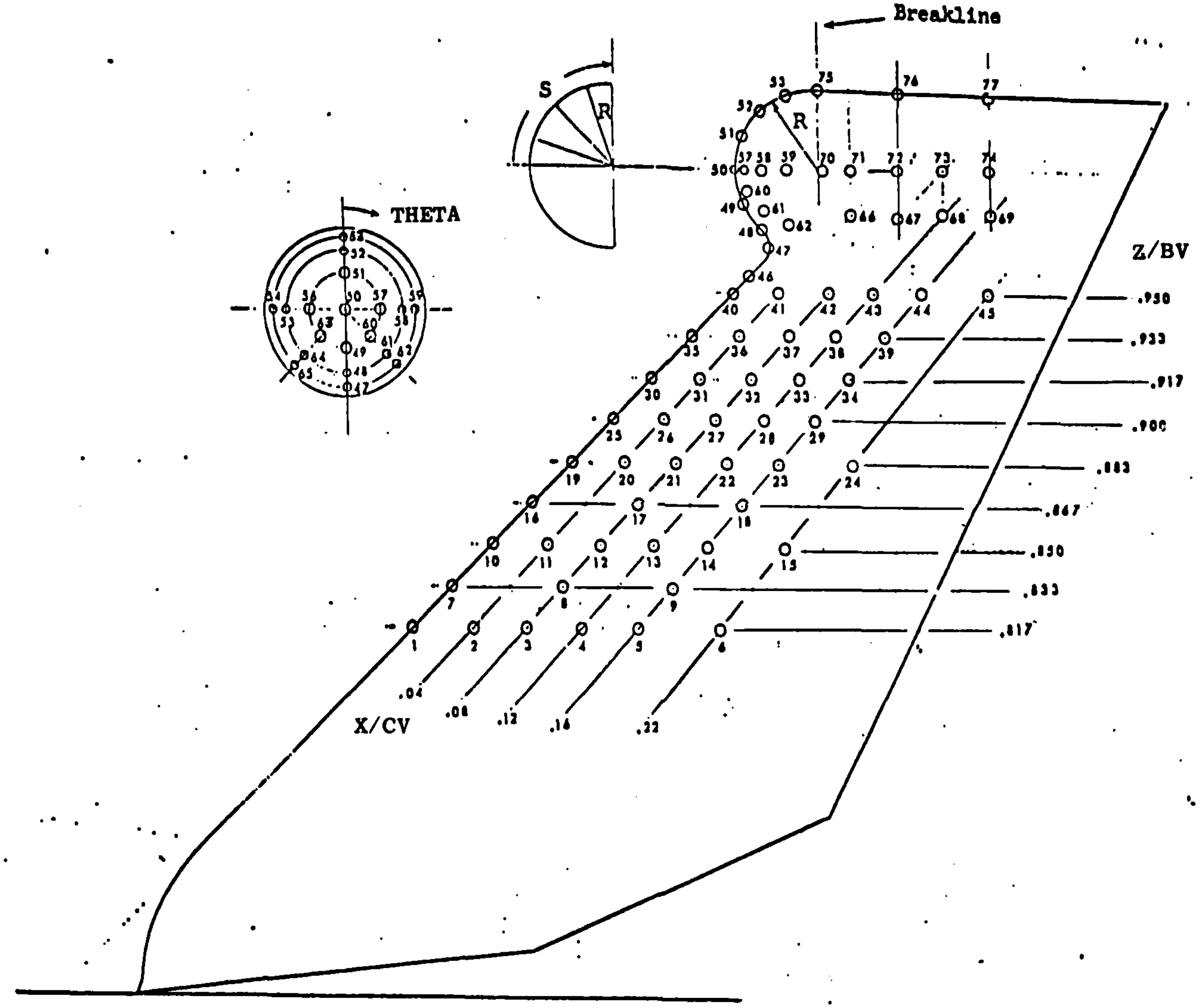
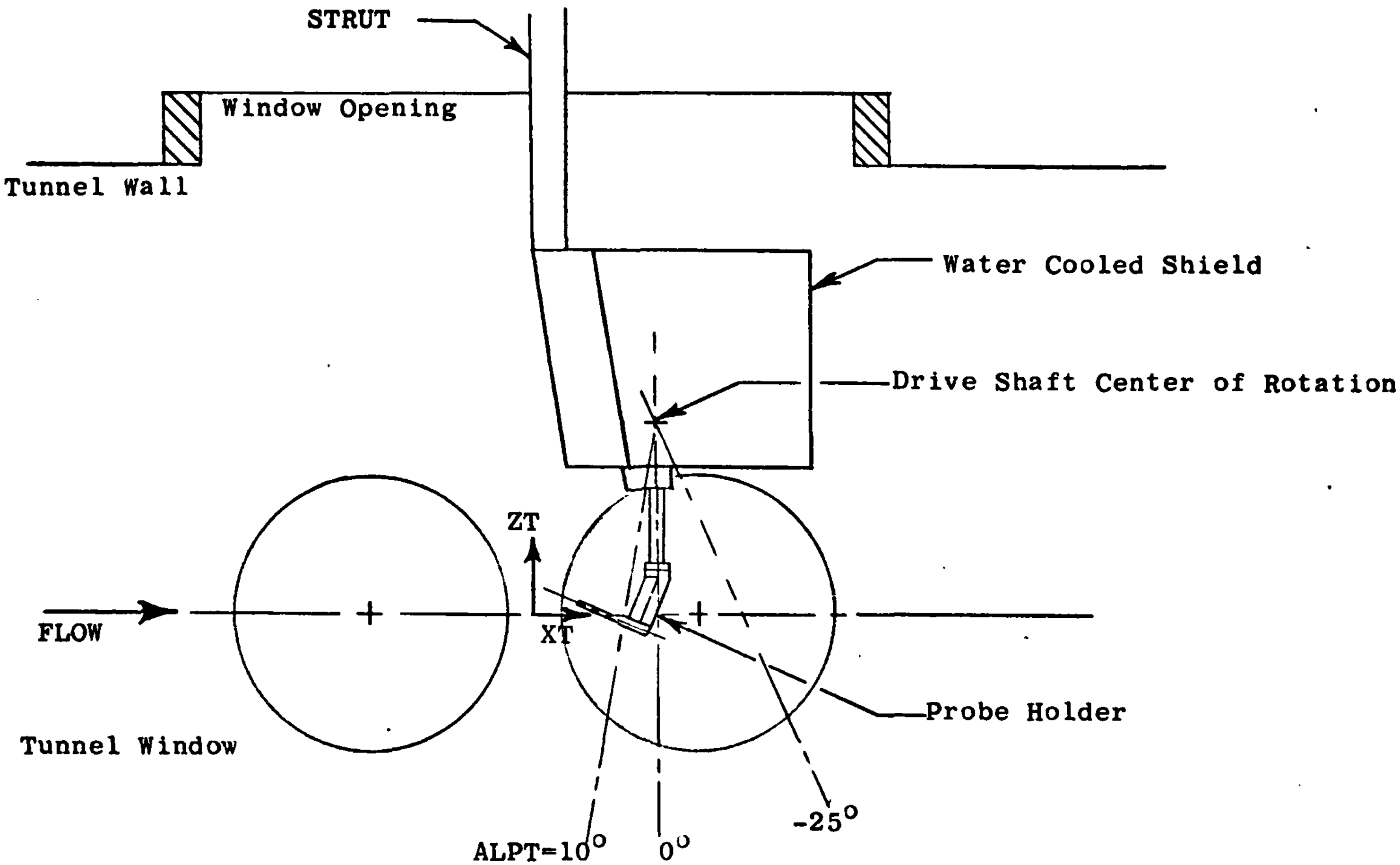
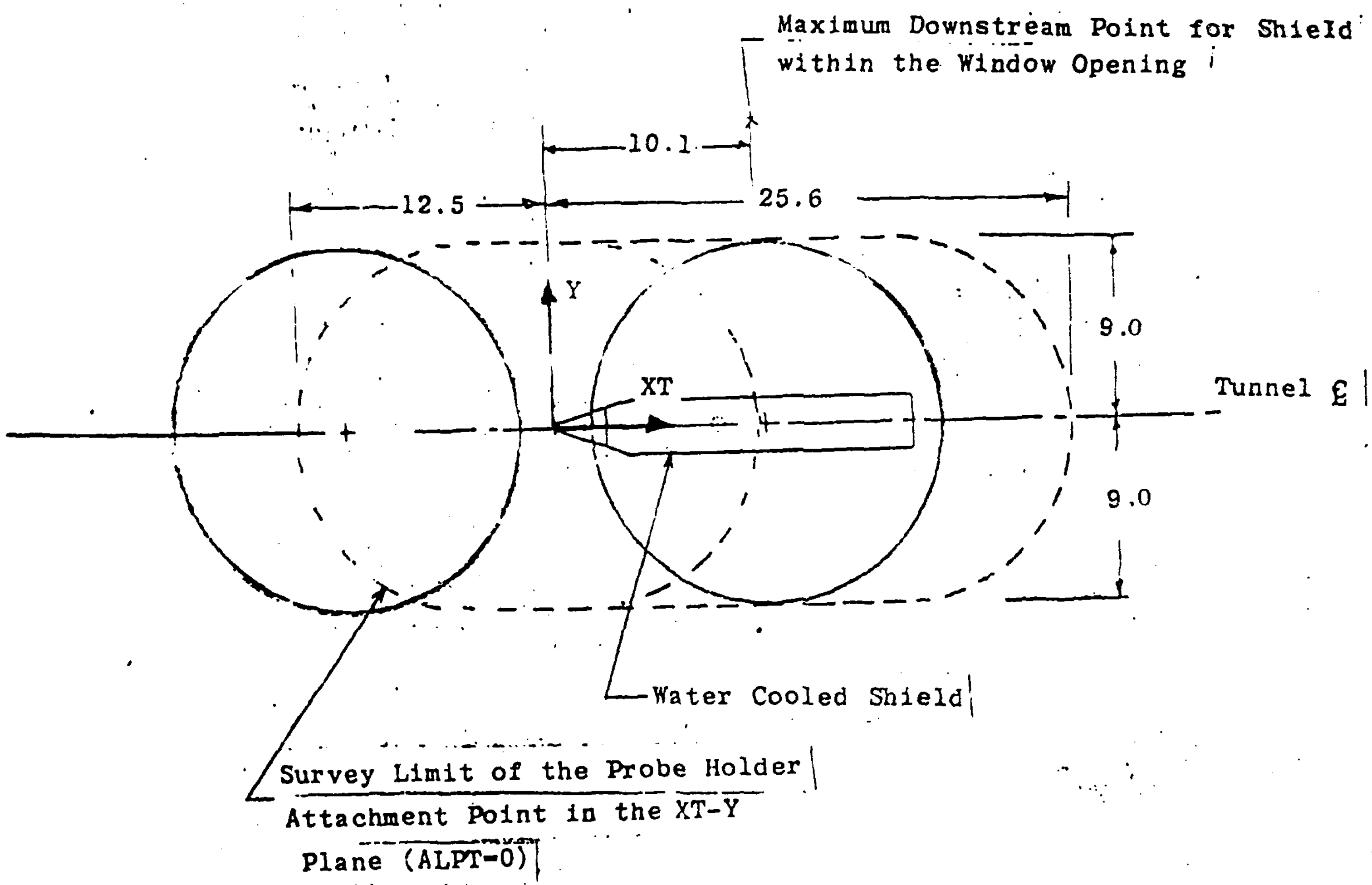


Fig. 11 Thermocouple Locations on a 0.0525 Scale Vertical Tail



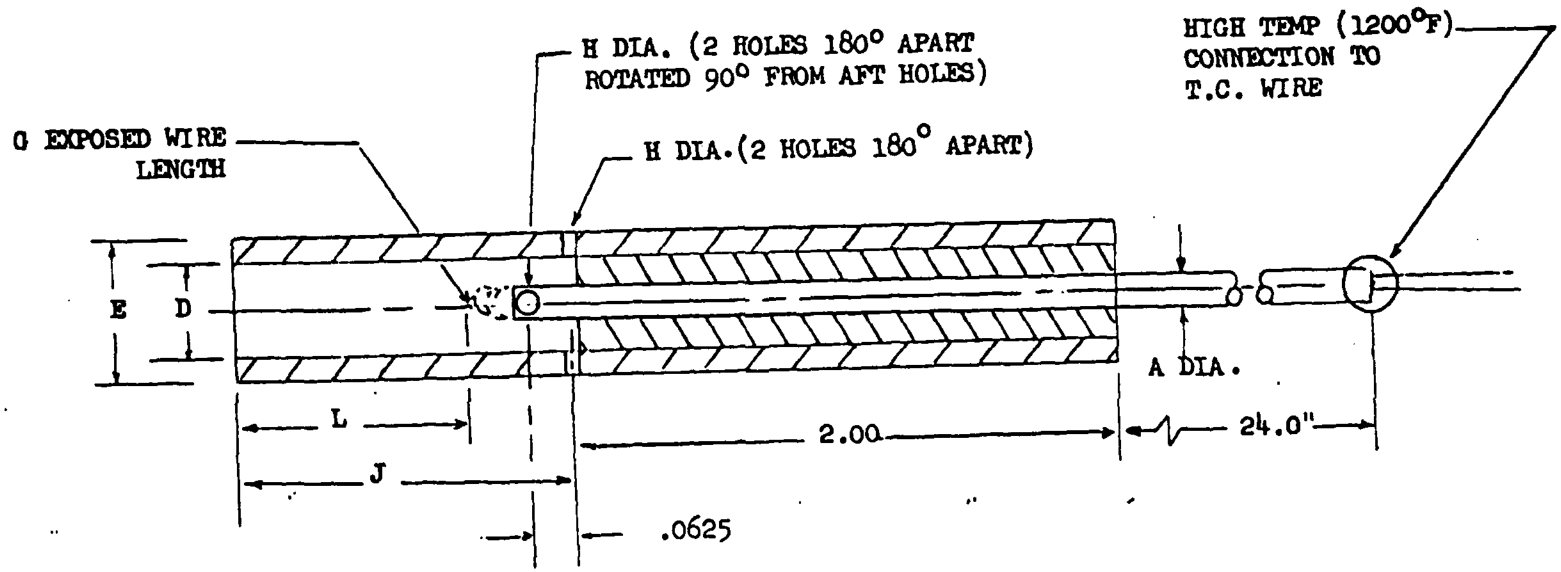
a. Side view

Fig. 12 Overhead Probe Survey Mechanism



b. Top View

Fig. 12 Concluded



A	D	E	H	G	J	L
0.020	0.056	0.060	0.020	0.250	0.668	0.112

Fig. 13 Shielded Thermocouple Probe

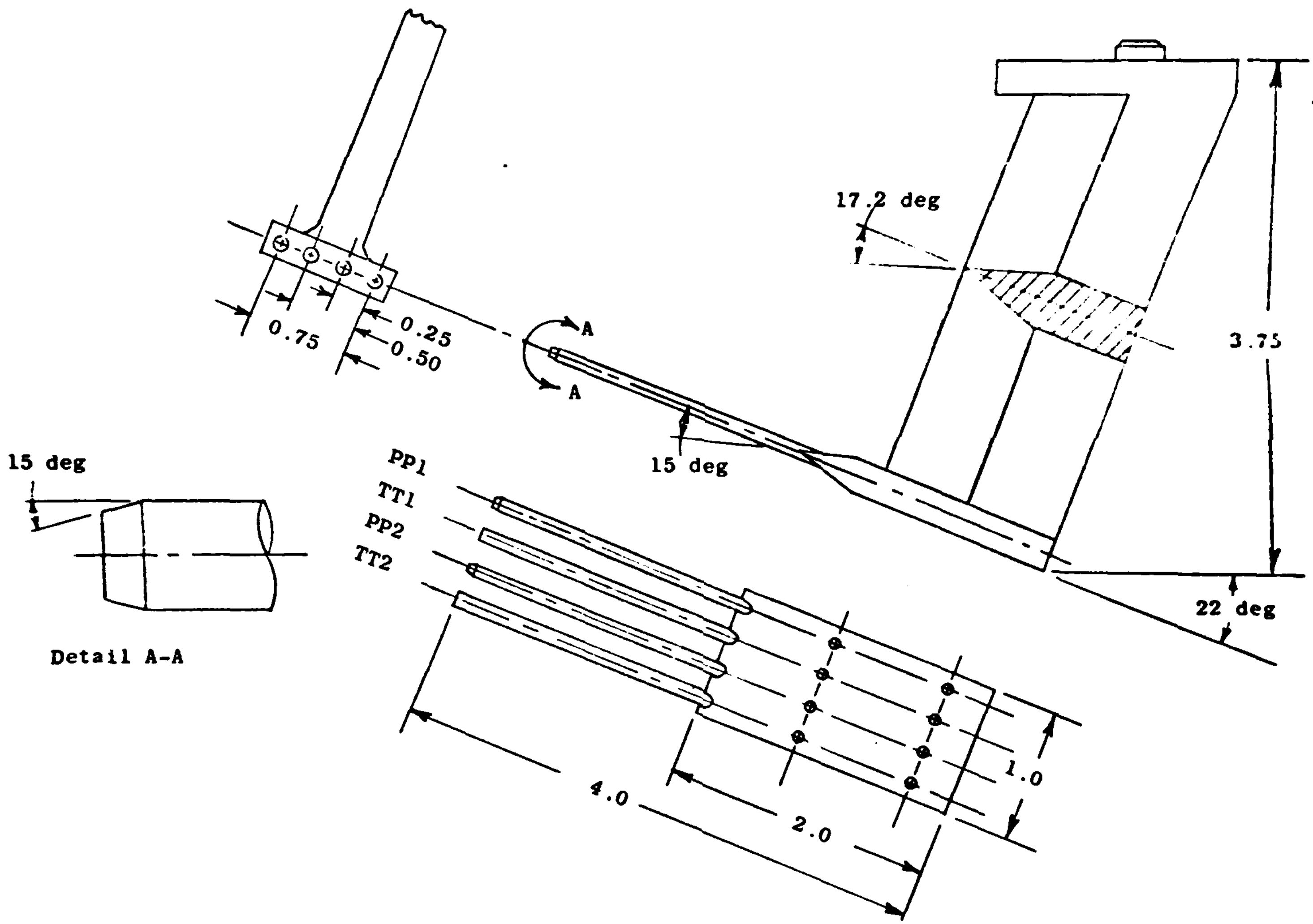


Fig. 14 Probe Holder

Fig. 15 Flow Field Probe Alignment with Optical Overlay

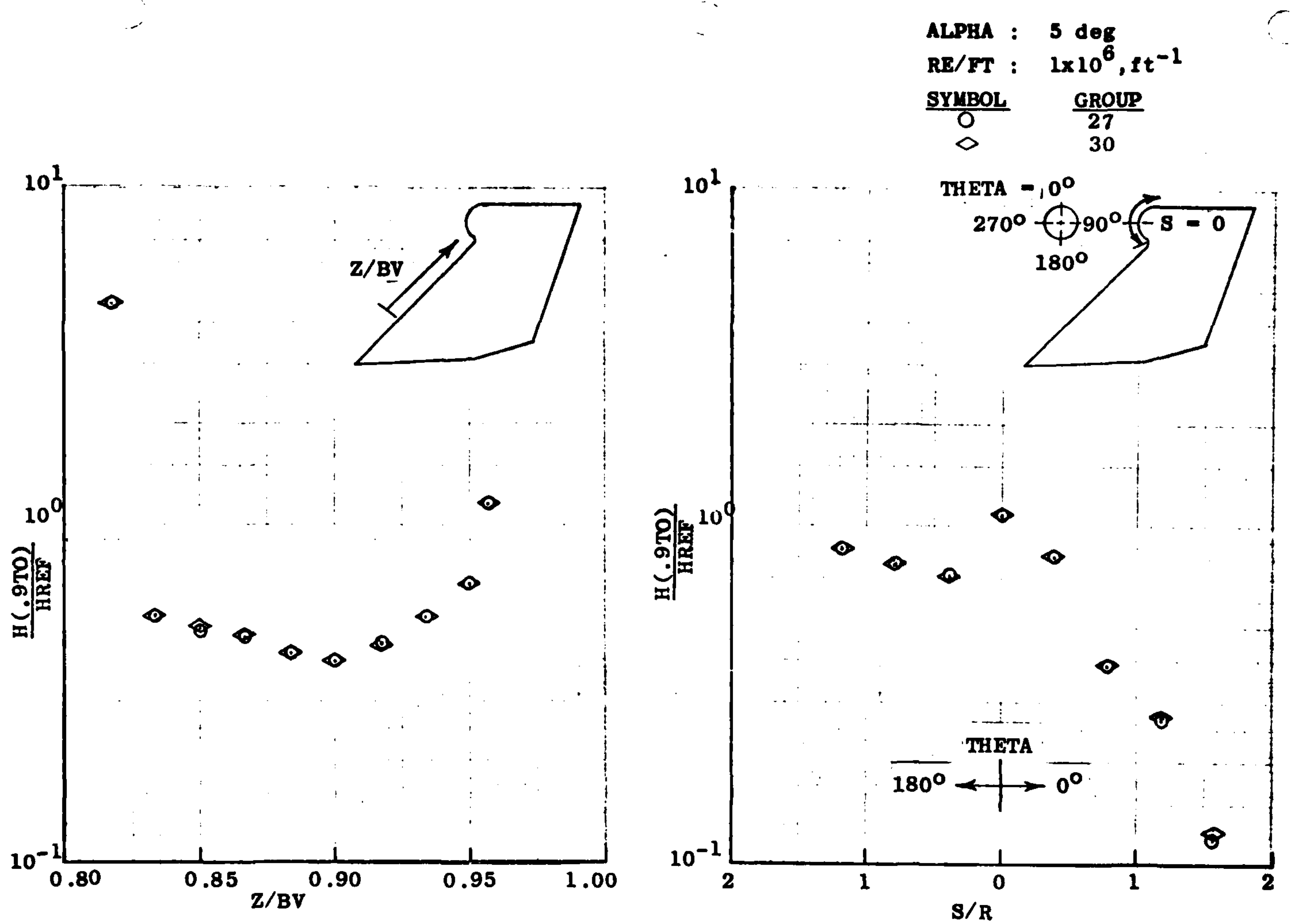
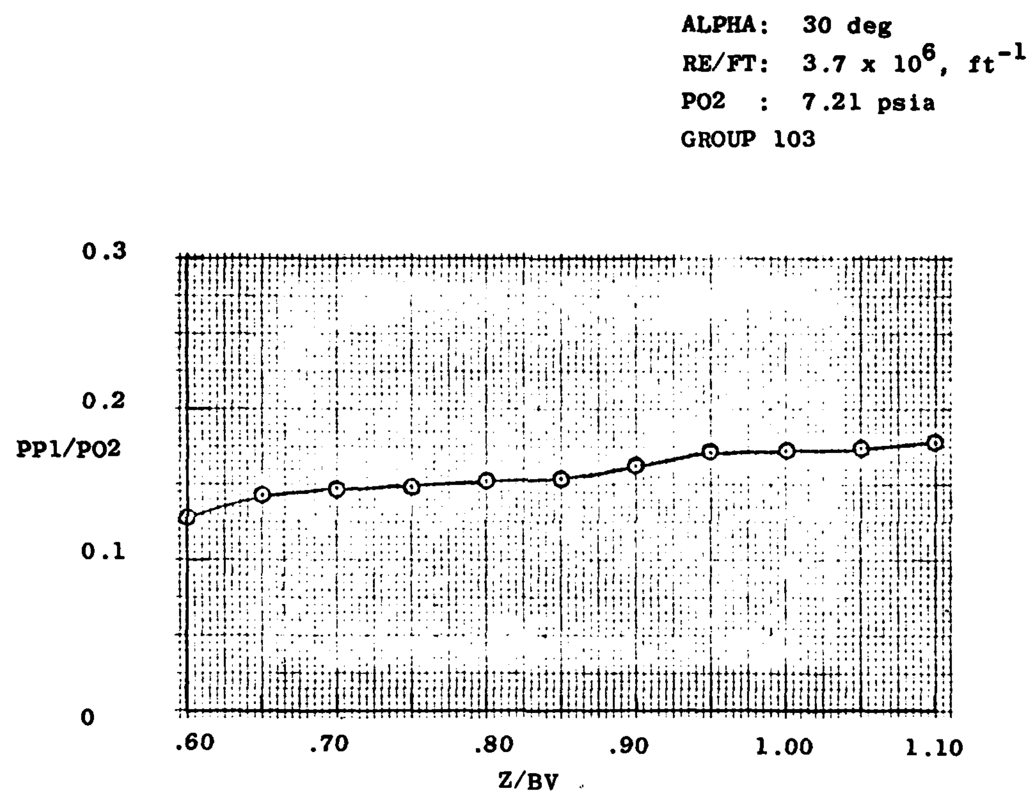
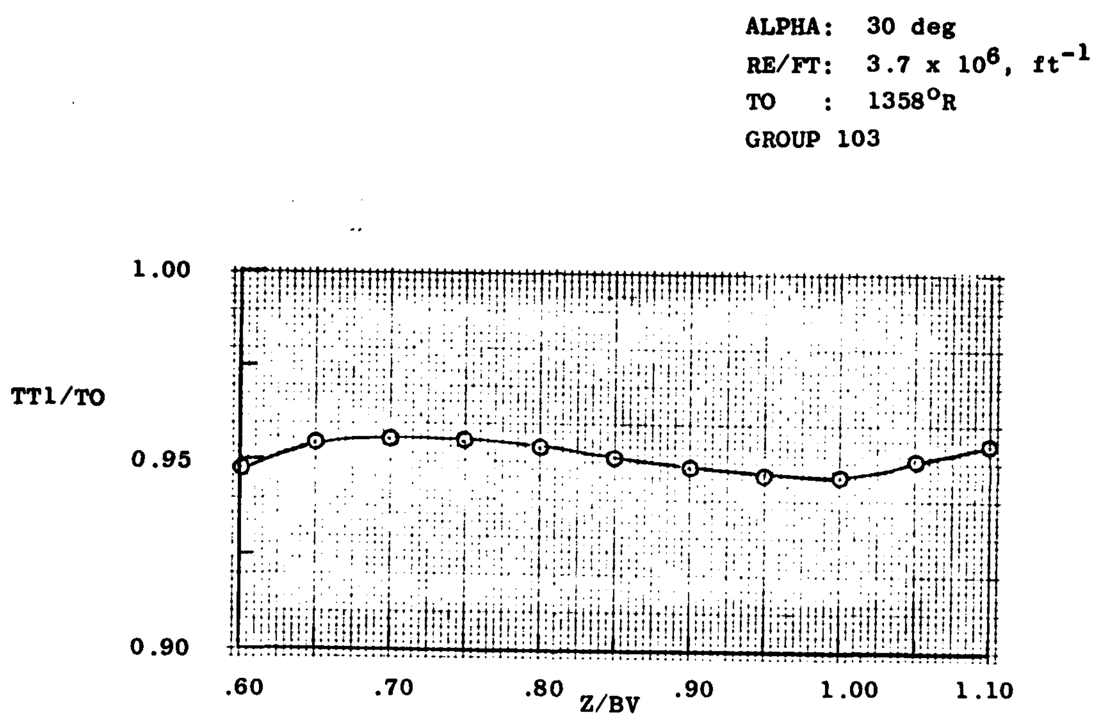


Fig. 16 Data Repeatability on Leading Edge of 0.0525 Scale Tail



a. Total pressure probe, PP1

Figure 17. Representation Probe Measurements



b. Total temperature probe, TT1

Figure 17. Concluded

APPENDIX II

TABLES

TABLE 1. ESTIMATED UNCERTAINTIES

a. Basic Measurements

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S) Percent of Reading	Precision Index (S) Unit of Measurement	Degree of Freedom	Bias (B) Percent of Reading	Bias (B) Unit of Measurement	Uncertainty $\pm(B + t_{95}S)$ Percent of Reading	Uncertainty $\pm(B + t_{95}S)$ Unit of Measurement	Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
ALPHA-SECTOR, deg		0.02	>30		0.01		±0.05	±15	Potentiometer	Digital Data Acquisition System A-D Converter	Heidenhain Rotary Encoder RD700
ALPT, deg		0.05	2		0.2		±0.4	±180			Inclinometer
b, in.	0+			3.0		3.0		0.030			Supplied by Rockwell
c_p, BTU lbm°R	0+			5.0		5.0		0.09			
PO, psia		0.02 0.11	>30 >30	0.25 0.25		±(0.25% + 0.04) ±(0.25% + 0.22)		0 - 200 200-1000	Bell & Howell Variable Capacitance Transducer	Digital Data System	Air Dead Weight Tester
PP1, psia		0.0002 0.002	>30		0.001 0.01	±0.0014 ±0.014		0 - 1 1 - 10	Druck	Digital Data Acquisition System Multiverter	Air Dead Weight Tester
PP2, psia		0.0002 0.002	>30		0.001 0.01	±0.0014 ±0.014		0 - 1 1 - 10			
ROLL-SECTOR, deg		0.06	>30		0.08		±0.20	±180	Potentiometer	Digital Data Acquisition System	Heidenhain Rotary Encoder RD700
TO, °F		1	>30	0.375		±(0.375% + 2°F)		750-900	CR-AL Thermocouple	Doric/Digital Acquisition System	Thermocouple Verification of NBS Conformity by Voltage Substitution
TT1, °F		1	>30	0.375		±(0.375% + 2°F)		450-900		Beckman A-D Converter and Digital Data Acquisition System	
TT2, °F		1	>30	0.375		±(0.375% + 2°F)		450-900			
T4, °F		1	>30	0.375		±(0.375% + 2°F)		50-400	CR-CN Thermocouple		
Y, in.		0.02	>30		0.05		0.09	0 - 1	Potentiometer	A-D Converter Digital Data Acquisition System	Precision Scale
ρ, lbm/in.^{3}	0+			1.0		1.0		490			Supplied by Rockwell

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
+Assumed to be zero

VB-16 (8/79)

TABLE 1. Concluded

b. Calculated Parameters

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT[a]							RANGE
	Precision Index (S)			Bias (B)		Uncertainty $\pm(B + t_{95}S)$		
	Percent of Reading	Unit of Measurement	Degree of Freedom	Percent of Reading	Unit of Measurement	Percent of Reading	Unit of Measurement	
ALPHA, deg		±0.04	>30		±0.02		±0.10	-5,5,30, 40
H(TO),H(.9TO), BTU/FT^2-SEC-$^\circ$R	±1.1		>30	±5.8		±8.0		All
M		0.015	>30		0[b]		0.03	7.90→ 7.94
		0.010	>30		0[b]		0.02	7.98→ 8.00
QDOT,BTU/FT^2-SEC	±0.6		>30	±5.8		±7.0		All
RE/FT,ft^{-1}	±0.53		>30	±0.44		±1.50		0.5x10^6 to 1.0x10^6
	±0.36		>30	±0.45		±1.17		2.0x10^6 to 3.7x10^6

[a]Abernethy, R. B. et al. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
[b]Assumed to be zero

VS-15a (9-75)

TABLE 2. Model Thermocouple Locations

a. 0.0175 Scale Vertical Tail

(CONSTANT SET 111)

TC No.	X/CV	Z/BV	b, inches	TC No.	X/CV	Z/BV	b, inches
1	0.10	.70	.015	22	0.00	0.85	.016
2	0.30		.021	23	0.10		.016
3	0.50		.021	24	0.20		.021
4	0.70		.021	25	0.30		.019
5	0.90		.020	26	0.40		.0195
6	0.00	.75	.018	27	0.50		.018
7	0.10		.020	28	0.70		.020
8	0.20		.021	29	0.00	0.90	.020
9	0.30		.020	30	0.10		.016
10	0.40		.021	31	0.30		.019
11	0.50		.020	32	0.50		.016
12	0.70		.020	33	0.70		.019
13	0.90		.020	34	0.90		.021
14	0.00	.80	.018	35	0.10	0.937	.016
15	0.10		.018	36	0.38	0.941	.023
16	0.20		.0225	37	0.60	0.925	.017
17	0.30		.020	38	0.70	0.949	.018
18	0.40		.020	39	0.80	0.949	.0195
19	0.50		.019	40	-0.13	0.973	.011
20	0.70		.020	41	0.00		.025
21	0.90		.020	42	0.18		.020
				43	0.10	1.00	.014

TABLE 2. Concluded

b. 0.0525 Scale Vertical Tail

(CONSTANT SET 211)

TC No.	X/CV	Z/BV	b, inches	TC No.	X/CV	Z/BV	b, inches
1	0.00	.817	.024	24	0.287	.883	.0226
2	0.052		.0203	25	0.00	.900	.019
3	0.104		.0201	26	0.052		.023
4	0.156		.0208	27	0.104		.020
5	0.209		.0225	28	0.156		.022
6	0.287		.0232	29	0.209		.0218
7	0.00	.833	.022	30	0.00	.917	.020
8	0.104		.0205	31	0.052		.0215
9	0.209		.0232	32	0.104		.0195
10	0.00	.850	.022	33	0.156		.021
11	0.052		.020	34	0.209		.0215
12	0.104		.0208	35	0.00	.933	.0223
13	0.156		.0232	36	0.052		.0221
14	0.209		.0235	37	0.104		.021
15	0.287		.0225	38	0.156		.0215
16	0.00	.867	.0223	39	0.209		.0228
17	0.104		.0218	40	0.00	.950	.0188
18	0.209		.0235	41	0.052		.0237
19	0.00	.883	.020	42	0.104		.0213
20	0.052		.0235	43	0.156		.022
21	0.104		.022	44	0.209		.0218
22	0.156		.023	45	0.287		.0215
23	0.209		.0228	46	0.00	.956	.021

TC No.	THETA, deg	S/R	b, inches	TC No.	THETA, deg	S/R	b, inches
47	180	1.178	.021	63	225	0.393	.018
48		0.785	.016	64		0.785	.020
49		0.393	.011	65		1.178	.022
50	0	0.00	.022	66		2.269	.0205
51		0.393	.021	67	-	2.89	.0188
52		0.785	.014	68	-	3.513	.0204
53		1.178	.0125	69	-	4.114	.0222
54	270	1.178	.020	70	90	1.63	.020
55		0.785	.023	71		1.996	.0198
56		0.393	.022	72		2.542	.020
57	90	0.393	.023	73		3.09	.023
58		0.785	.023	74		3.619	.0232
59		1.178	.020	75	0	1.571	.0215
60	135	0.393	.024	76		2.542	.022
61		0.785	.024	77		3.637	.023
62		1.178	.024				

TABLE 3. Test Summary

a. Flow Angularity Data Groups, OH-102A Test

ALPHA, deg	ROLL-SECTOR, deg	RE/FT x 10^{-6}, ft^{-1}				
		0.5	1.0	2.0	3.0	3.7
30	0	3		6	1	2
	90	10	24	34,35*	17	25
	180	11	18			26
32.5	0			9		
	180	16	21,22			29
35	0	5		8		
	180	13	19			27,32
37.5	180	15	23	33		30
40	0	4,14		7		
	180	12	20	36*		28

*Tufts on model
GROUP 31 - no pictures

TABLE 3. Continued

b. Heat-Transfer Data Groups, OH-400 Test

CONSTANT SET	SILTS SCALE	ALPHA, deg.	RE/FT x 10^{-6}, ft^{-1}				
			0.5	1.0	2.0	3.0	3.7
111	0.0175	-5	77	73	69		
↓	↓	0	76	72	68		
↓	↓	5	75,78	71,74	67,70		
↓	↓	30	79	64	60,63	57	50*,52, 54
↓	↓	35	80	65	61	58	51*,53, 55
↓	↓	40	81	66	62	59	56
211	0.0525	-5	33	29	22,25		
↓	↓	0	32	28	21,24		
↓	↓	5	31,34	27,30	19*,20, 23,26		
↓	↓	30	16	12,15*	9	6	1*,2, 3
↓	↓	35	17	13	10	7	4
↓	↓	40	18	14	11	8	5

*Vertical tail covered during model injection

TABLE 3. Continued

c. Oil Flow Data Groups, OH-400 Test

SILTS SCALE	ALPHA, deg	RE/FT X 10^{-6}, ft^{-1}				
		0.5	1.0	2.0	3.0	3.7
0.0175	-5		96			93
	0		95			92
	5		94			91
	30		82			86,87,90
	35		83			88
	40		84,85			89
0.0525	-5		99			41
	0		98			40
	5		97			35→39
	30		46,49			42
	35		47			43
	40		48			44,45

TABLE 3. Concluded

d. Flow Field Probe Data Groups, OH-400 Test

ALPHA, deg	Y, in.	RE/FT x 10^{-6}, ft^{-1}				
		0.5	1.0	2.0	3.0	3.7
Freestream Calibration*	0	120	115	111	106	101
30	0	121	116	112	107	103
↓	-.25			124		
35	0	122	117	113	108	104
40	0	123	118	114	109	105
	-.25		119			
↓	-.5				110	

Delete Groups 100, 102

*Model removed from tunnel

TABLE 4. Probe Angles at the Vertical Tail Leading Edge

$z/_{BV}$	RE/FT	0.5×10^6			1.0×10^6			2.0×10^6			3.0×10^6			3.7×10^6		
	ALPHA	30	35	40	30	35	40	30	35	40	30	35	40	30	35	40
.60		47	42	37	38	42	37	18	34	35	17	24	33	16	18	32
.65		47	42	37	28	42	37	16	20	34	14	18	30	12	16	27
.70		43	42	37	23	40	37	16	12	25	15	14	23	14	16	22
.75		39	42	37	19	35	34	15	8	21	13	12	19	12	14	17
.80		36	38	37	20	27	28	16	7	18	15	11	16	14	13	14
.85		36	34	32	21	20	27	17	7	15	15	11	13	13	13	11
.90		35	30	28	20	19	24	18	7	15	16	11	11	14	14	9
.95		31	24	23	19	16	22	18	7	12	15	11	10	13	13	8
1.00		30	20	22	21	16	18	18	7	11	16	11	9	15	13	8
1.05		27	17	21	22	15	16	17	7	9	16	11	8	17	13	8
1.10		27	17	20	22	17	14	16	7	7	16	11	7	16	13	8

NOTE: Probe angle = Flow angle, see Fig. 3

Probe Angle (typical), deg

APPENDIX III

REFERENCE HEAT-TRANSFER CONDITIONS

In presenting heat-transfer coefficient results, it is convenient to use reference coefficients to normalize the data. Equilibrium stagnation point values derived from the work of Fay and Riddell* were used to normalize the data obtained in this test. These reference coefficients are given by:

$$\mathrm{HREF} = \frac{8.17173(\mathrm{PO2})^{0.5}\,(\mathrm{MUO})^{0.4}\left[1 - \frac{(\mathrm{P\text{-}INF})}{\mathrm{PO2}}\right]^{0.25}\left[0.2235+(1.35\times10^{5})(\mathrm{TO}+560)\right]}{(\mathrm{RN})^{0.5}\,(\mathrm{TO})^{0.15}}$$

$$\mathrm{STFR} = \frac{\mathrm{HREF}}{(\mathrm{RHO\text{-}INF})\,(\mathrm{V\text{-}INF})\left[0.2235 + 1.35 \times 10^{-5}\,(\mathrm{TO} + 560)\right]}$$

*Fay, J. A., and Riddell, F. R., "Theory of Stagnation Point Heat Transfer in Dissociated Air," Journal of the Aeronautical Sciences, Vol. 25, No. 2, February 1958.

APPENDIX IV

SAMPLE TABULATED DATA

APP IX

ARO, INC. - AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE

NASA/RI OH400 HEATING TEST

DATE COMPUTED 7-NOV-79
TIME COMPUTED 11:25:21
DATE RECORDED 9-OCT-79
TIME RECORDED 0:50:31
PROJECT NUMBER V41B-65

GROUP CONSTANT	MODEL	SILTS SCALE	MACH NO	PO,PSIA	TO,DEGR	ALPHA-PREBEND	ALPHA-SECTOR	ROLL-SECTOR	ALPHA	YAW
81 SET 111	92-0	0.0175	7.90	115.5	1250.7	37.00	3.02	0.18	40.02	-0.01

T-INF (DEGR)	P-INF (PSIA)	Q-INF (PSIA)	V-INF (FT/SEC)	RHO-INF (LBM/FT3)	MU-INF (LB-SEC/FT2)	RE/FT (FT-1)	HREF (RN= 0.0175FT)	STFR (RN= 0.0175FT)	SWITCH POSITION	CONFIG
92.77	0.013	0.561	3730.	3.734E-04	7.465E-08	5.798E+05	1.834E-02	5.311E-02	1	1

TC NO	TW (DEGR)	DTWDT (DEG/S)	QDOT (BTU/ FT2-S)	H(TO) (BTU/FT2 S-DEGR)	H(TO)/ HREF	H(.90TO) (BTU-FT2- S-DEGR)	H(.90TO)/ HREF	THERMOCOUPLE LOCATIONS X/CV	Z/BV	SKIN THICKNESS
1	535.9	2.672	0.179	2.506E-04	0.0137	3.038E-04	0.0166	0.1000	0.7000	0.0150
2	534.5	0.956	0.090	1.252E-04	0.0068	1.517E-04	0.0083	0.3000	0.7000	0.0210
3	534.3	0.567	0.053	7.421E-05	0.0040	8.990E-05	0.0049	0.5000	0.7000	0.0210
4	534.0	0.411	0.039	5.376E-05	0.0029	6.512E-05	0.0036	0.7000	0.7000	0.0210
5	533.8	0.501	0.045	6.240E-05	0.0034	7.559E-05	0.0041	0.9000	0.7000	0.0200
6	539.2	4.119	0.332	4.666E-04	0.0254	5.661E-04	0.0309	0.0000	0.7500	0.0180
7	536.1	3.077	0.275	3.850E-04	0.0210	4.667E-04	0.0754	0.1000	0.7500	0.0200
8	531.5	1.754	0.165	2.298E-04	0.0125	2.784E-04	0.0152	0.2000	0.7500	0.0210
9	533.8	1.173	0.105	1.461E-04	0.0080	1.770E-04	0.0097	0.3000	0.7500	0.0200
10	534.6	0.968	0.091	1.268E-04	0.0069	1.537E-04	0.0084	0.4000	0.7500	0.0210
11	534.8	0.834	0.075	1.041E-04	0.0057	1.261E-04	0.0069	0.5000	0.7500	0.0200
12	534.2	0.458	0.041	5.706E-05	0.0031	6.912E-05	0.0038	0.7000	0.7500	0.0200
13	534.2	0.632	0.056	7.878E-05	0.0043	9.544E-05	0.0052	0.9000	0.7500	0.0200
14	539.6	3.933	0.317	4.450E-04	0.0243	5.399E-04	0.0294	0.0000	0.8000	0.0180
15	DELETE									
16	534.1	1.988	0.200	2.788E-04	0.0152	3.378E-04	0.0184	0.2000	0.8000	0.0225
17	534.0	1.348	0.120	1.680E-04	0.0092	2.035E-04	0.0111	0.3000	0.8000	0.0200
18	533.9	1.182	0.106	1.472E-04	0.0080	1.784E-04	0.0097	0.4000	0.8000	0.0200
19	533.7	1.098	0.093	1.299E-04	0.0071	1.573E-04	0.0086	0.5000	0.8000	0.0190
20	534.1	0.709	0.063	8.841E-05	0.0048	1.071E-04	0.0058	0.7000	0.8000	0.0200
21	534.3	0.669	0.060	8.345E-05	0.0046	1.011E-04	0.0055	0.9000	0.8000	0.0200
22	541.3	4.412	0.316	4.461E-04	0.0243	5.416E-04	0.0295	0.0000	0.8500	0.0160
23	538.2	3.366	0.241	3.383E-04	0.0184	4.103E-04	0.0224	0.1000	0.0500	0.0160
24	535.3	2.021	0.190	2.651E-04	0.0145	3.212E-04	0.0175	0.2000	0.0500	0.0210
25	534.9	1.612	0.137	1.911E-04	0.0104	2.316E-04	0.0126	0.3000	0.0500	0.0190
26	DELETE									
27	534.7	1.362	0.110	1.530E-04	0.0083	1.854E-04	0.0101	0.5000	0.8500	0.0180
28	534.5	1.018	0.091	1.270E-04	0.0069	1.539E-04	0.0084	0.7000	0.8500	0.0200
29	537.0	4.428	0.396	5.551E-04	0.0303	6.731E-04	0.0367	0.0000	0.9000	0.0200
30	DELETE									
31	535.3	1.999	0.170	2.373E-04	0.0129	2.876E-04	0.0157	0.3000	0.9000	0.0190
32	535.7	1.600	0.114	1.600E-04	0.0087	1.939E-04	0.0106	0.5000	0.9000	0.0160
33	535.3	1.065	0.090	1.264E-04	0.0069	1.531E-04	0.0084	0.7000	0.9000	0.0190

1. Heat-Transfer Data

APP 2

ARO, INC. - AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE

DATE COMPUTED 7-NOV-79
TIME COMPUTED 14:12:52
DATE RECORDED 9-OCT-79
TIME RECORDED 23:59: 4
PROJECT NUMBER V41B-65

GROUP	CONSTANT	MODEL	SILTS SCALE	MACH NO	PO,PSIA	TO,DEGR	ALPHA-PREBEND	ALPHA-SECTOR	ROLL-SECTOR	ALPHA	YAW
104	SET 0	92-0	0.0175	8.00	846.8	1350.7	37.00	-1.94	0.08	35.06	0.00

T-INF (DEGR)	P-INF (PSIA)	Q-INF (PSIA)	V-INF (FT/SEC)	RHO-INF (LBM/FT3)	MU-INF (LB-SEC/FT2)	RE/FT (FT-1)	HREF (RN= 0.0175FT)	STFR (RN= 0.0175FT)	SWITCH POSITION	CONFIG
97.87	0.067	3.886	3880.	2.392E-03	7.876E-08	3.662E+06	4.893E-02	2.115E-02		3

Z/RV	Y(PP1)	FLOW ANGLE	PP1,PSIA	PP2,PSIA	TT1,R	TT2,R
0.65	-0.030	15.940	1.213	1.478	1341.62	1298.07
0.70	-0.020	15.940	1.437	1.736	1346.36	1307.40
0.75	-0.030	13.960	1.471	1.847	1339.08	1344.16
0.80	-0.030	12.860	1.440	1.799	1332.99	1354.31
0.85	-0.030	12.850	1.421	1.737	1330.11	1346.19
0.90	-0.020	13.860	1.400	1.665	1326.21	1340.86
0.95	0.000	12.910	1.388	1.607	1324.18	1339.42
1.00	-0.020	12.900	1.384	1.572	1323.08	1338.74
1.05	0.000	12.910	1.381	1.532	1321.47	1337.47
1.05	-0.020	12.900	1.373	1.498	1320.28	1336.03
1.10	-0.020	12.900	1.370	1.499	1370.28	1336.03

2: Flow Field Probe Data

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DTIC